The Institution of Engineering and Technology

National Aeronautics and Space Administration

Current Status and Future Plans for Electric Motors and Drives at NASA

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Why Electric Aero-Propulsion?

- Why electric?
  - Fewer emissions
  - Quieter flight
  - Fuel savings
  - New mobility options
  - Better utilization of infrastructure

Electric Aero-Propulsion Benefits

$$\text{Benefits} \sim \frac{\left(\frac{L}{D}\eta\text{prop}\right)_{\text{E}}}{\left(\frac{L}{D}\eta\text{prop}\right)_{\text{AC}}}$$

- High Bypass Ratio (BPR)
  - Enabled by de-coupling the shaft speeds and inlet/outlet areas
  - 4-8% improvement in propulsive efficiency expected for fully turboelectric propulsion (Felder, Brown)
- Boundary Layer Ingestion (BLI)
  - Reduces drag by reenergizing the wake
  - 3-8% improvement in propulsive efficiency expected for fully turboelectric propulsion (Felder, Brown)

ηprop

- Lift-to-Drag (L/D) Improvements
  - Distributed propulsion improves wing flow circulation control
  - Up to 8% improvement expected (Wick)

$\frac{L}{D}$

(Felder and Brown, NASA)

System Level Benefits Depend on Component, Powertrain, and Vehicle Optimization

EAP Vehicle Class

NASA and industry studies have shown that EAP concepts can reduce energy use, carbon and nitrogen oxide emissions, and direct operating costs resulting in benefits for both the public and the airline operators.

NASA and its industry partners have identified turboprops, regional jets, and single aisle aircraft serving the thin-haul (very short flights), regional, and single-aisle markets as targets of opportunity for this technology.

To turn the promise of EAP benefits into reality, NASA's Aeronautics Research Mission Directorate has made a critical commitment to demonstrate practical vehicle-level integration of megawatt-class EAP systems, leveraging advanced airframe systems to reinvigorate the regional and emerging smaller aircraft markets, and to strengthen the single-aisle aircraft market.

Market:
On demand mobility

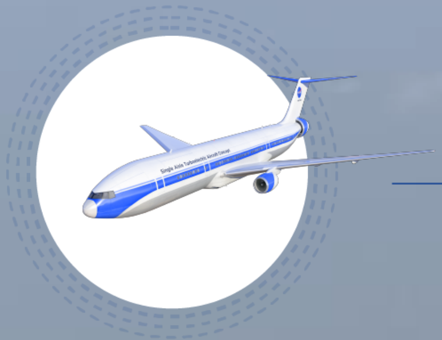
Potential Impact:
New mobility capacity

Market:
Regional

Potential Impact:
Revitalization of smaller routes

Market:
Regional

Potential Impact:
Increased point to point regional routes

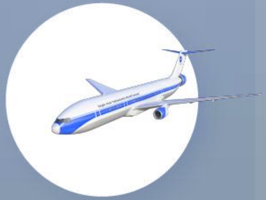


Market:
National/International

Potential Impact:
Fuel burn and emissions reduction

MW-CLASS Vehicle Parameters

NASA is advancing Electrified Aircraft Propulsion (EAP) technology across a variety of markets, ranges, aircraft sizes, VTOL/CTOL configurations and electrical power levels. Fully electric, hybrid, and turboelectric are potential EAP system configurations. Electrified aircraft propulsion impacts vary on aircraft design, depending on the key requirements of the market the vehicle is intended to serve.

	MARKET	AIRCRAFT	PASSENGERS	SPEED	RANGE	POWER	WASTE HEAT
	On demand mobility	VTOL	1-19	~50-200 mph	~25-200 miles	~1 MW	~200 kw heat
	Regional	General Aviation / Small Turboprop	1-19	~150-200 mph	~100-500 miles	~1 MW	~200 kw heat
	Regional	Regional Turboprops & Turbofans	20-150	~300-400 mph	~500-1500 miles	1-5 MW	~200 kw-1MW heat
	National/ International	Single Aisle	150+	~500-650 mph	~1500-7000 miles	3-30 MW	~600 kw-6MW heat

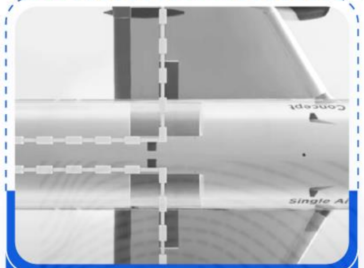
NASA EAP REPRESENTATIVE ACTIVITIES

NASA has executed a plethora of EAP activities over the last 10 years and is in the process of advancing the future of sustainable flight. Work spans from fundamental research to flight demonstrations.

X-57, 100kW class flight demo of all electric distributed propulsion.

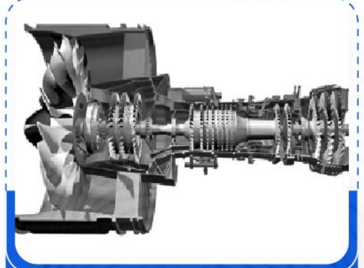
Revolutionary Vertical Lift Technology Studies of Electric, Hybrid, Turboelectric Concepts and Technology.

Electrified Powertrain Flight Demo – ground & flight demonstration of integrated MW-class powertrain.



Advanced Air Transport Technology/Propulsion & Power Subproject - powertrain technology

Transformational Tools & Technology – EAP materials & modeling.

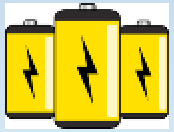


Hybrid Thermally Efficient Core (HyTEC)

Advanced turbine engine technologies in a high-power-density core.

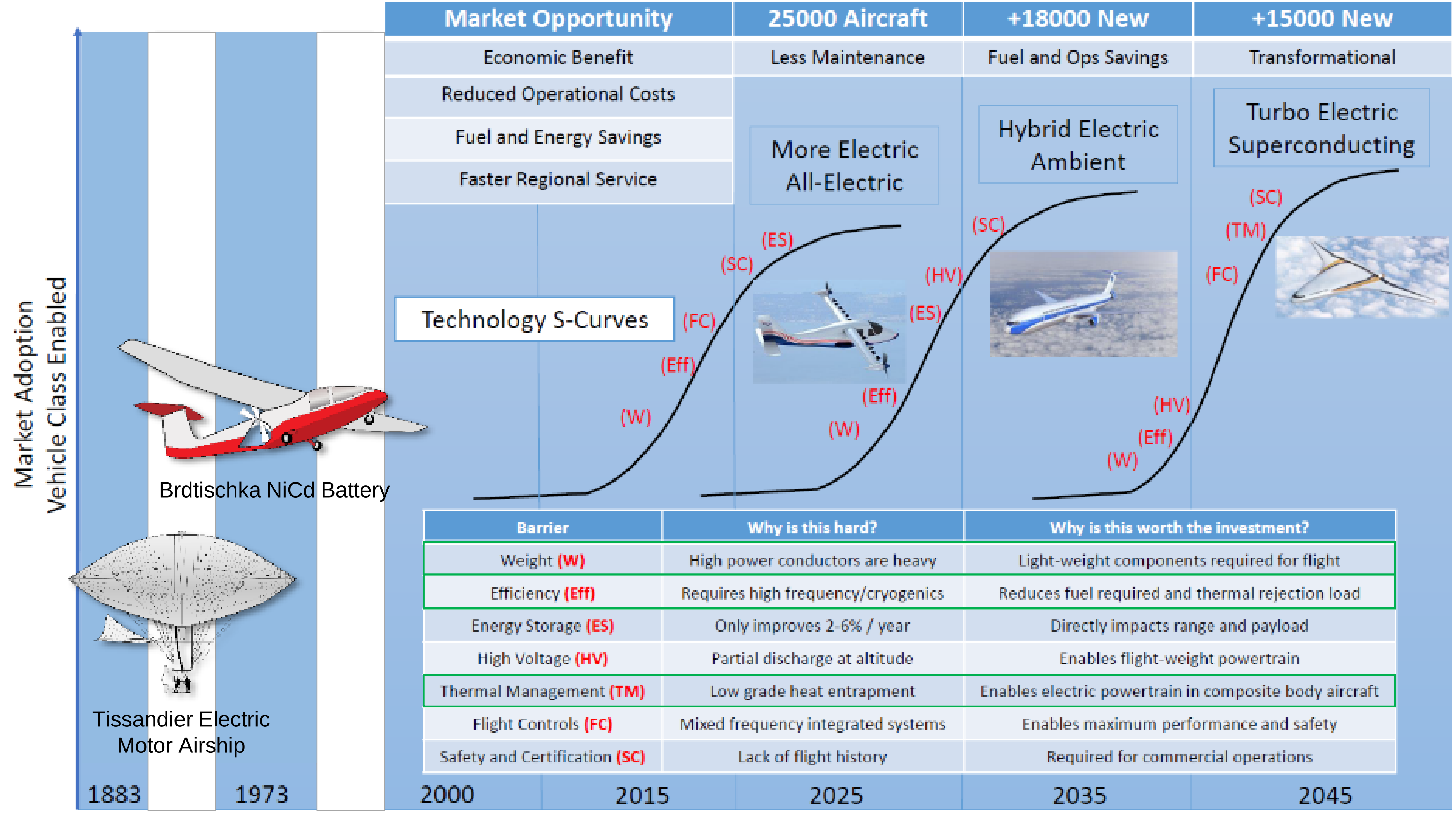
SUSAN – A 20 MW hybrid-electric aircraft concept study featuring a single aft engine with distributed wing-mounted propulsors.

EAP Ecosystem

	Electrical Energy Production	Electric Distribution	Energy Storage	Integrated Designs	System Testing & Evaluation	Certification	End User/ Buyer
DoD				✓	✓		✓
DOE	✓	✓	✓				
ARPA-E	ASCEND REEACH	CIRCUITS BREAKERS	✓				
FAA						✓	
NASA	Turbogen SOFC	Fault and Thermal	✓ SPACE	✓	✓	Flight Demos	
Engine Companies				✓	✓		
Airframers				✓	✓		
Operators							✓
Energy and Transport Industry	✓	✓	✓				

Technology Adoption S-Curves



Barrier	Why is this hard?	Why is this worth the investment?
Weight **(W)**	High power conductors are heavy	Light-weight components required for flight
Efficiency **(Eff)**	Requires high frequency/cryogenics	Reduces fuel required and thermal rejection load
Energy Storage **(ES)**	Only improves 2-6% / year	Directly impacts range and payload
High Voltage **(HV)**	Partial discharge at altitude	Enables flight-weight powertrain
Thermal Management **(TM)**	Low grade heat entrapment	Enables electric powertrain in composite body aircraft
Flight Controls **(FC)**	Mixed frequency integrated systems	Enables maximum performance and safety
Safety and Certification **(SC)**	Lack of flight history	Required for commercial operations

Research addresses weight, efficiency, thermal, and fault management technology barriers.

Technology Maturation

Advancing Technical & Integration Readiness

Increasing TRL, can decrease projected system benefits!

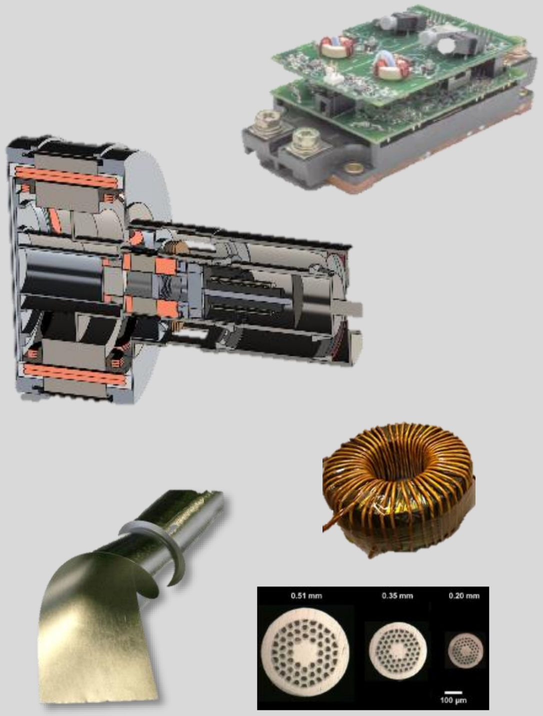
1

- **Concept Vehicles**
- **Technology Gap Assessments**
- **Key Performance Parameter Identification**
- **Market Research**
- **FMECA Studies**

TRL 1-2

2

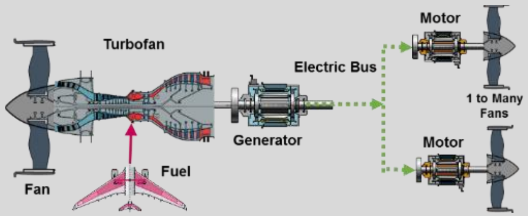
- **Subsystems**
- **Components**
- **Devices**
- **Enabling Materials**

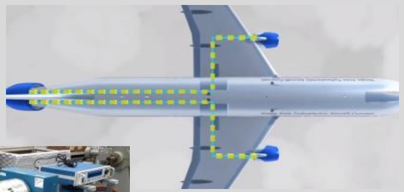


TRL ~3

3

- **Ground Testing**
- **Integrated systems**





TRL ~4

4

- **Flight Experiments in relevant environment**
- **UAM Grand Challenges**

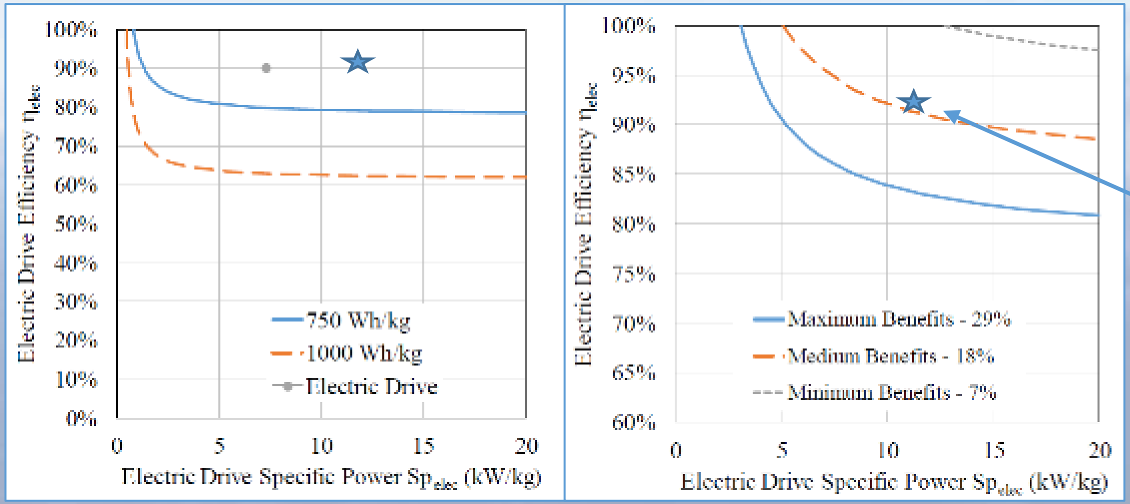
- Key data informing product decisions
- Knowledge to support certification
- Learning to inform further fundamental research

TRL 5-6

Powertrain Technology Requirements

- MW-Scale Transport Class Powertrain Requirements:

Break-even Points

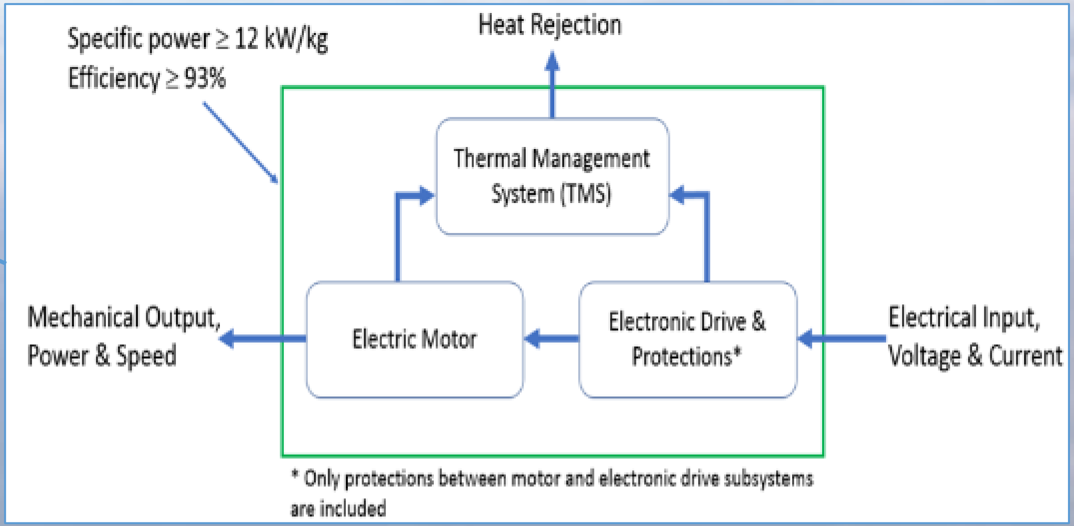


Parallel Hybrid

Turbo-electric

(Jansen, NASA)

ARPA-E ASCEND Powertrain



Ambient Motor Requirements

Key Performance Metrics	Specific Power (kW/kg)	Efficiency (%)
Goal	13.2	96

Ambient Inverter Requirements

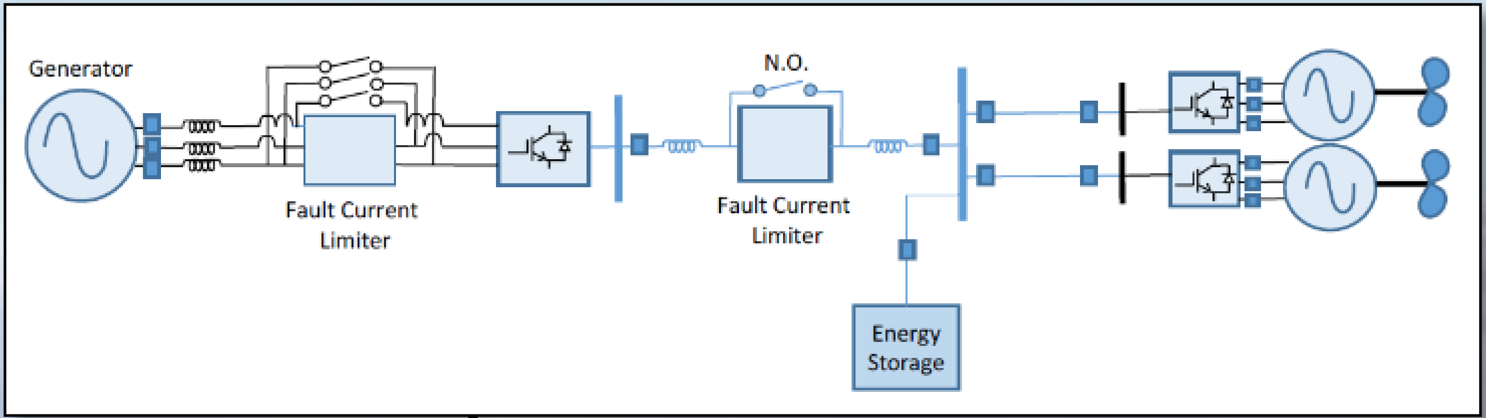
Key Performance Metrics	Specific Power (kW/kg)	Efficiency (%)
Minimum	12	98.0
Goal	19	99.0
Stretch Target	25	99.5

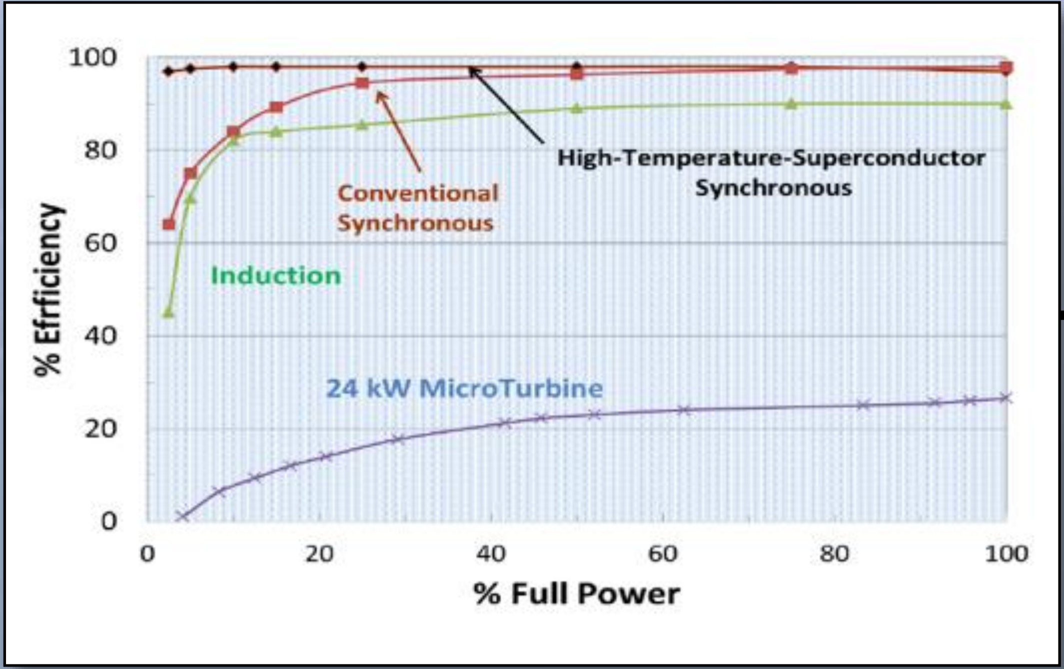
Cryogenic Inverter Requirements

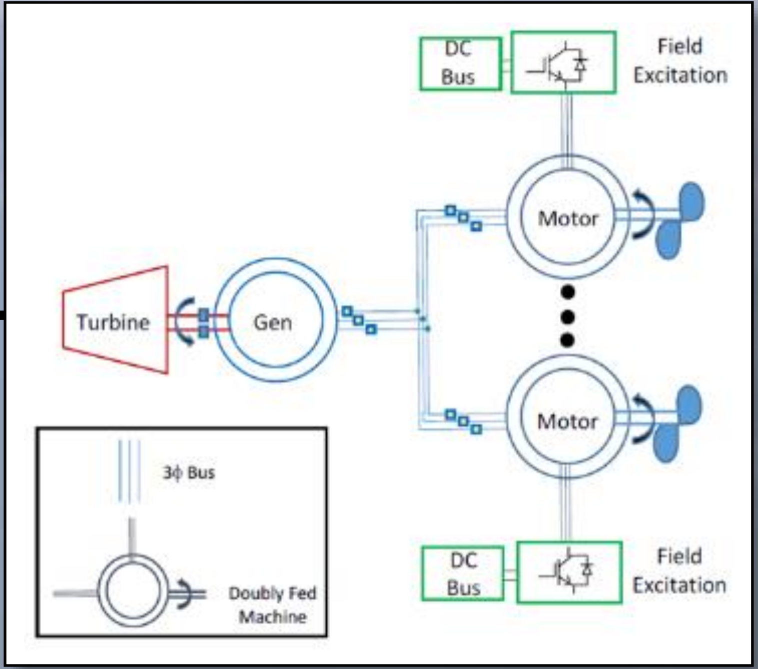
Key Performance Metrics	Specific Power (kW/kg)	Efficiency (%)
Minimum	17	99.1
Goal	26	99.3
Stretch Target	35	99.4

Electric Propulsion Machine Options

- Fully Superconducting
- Partially Superconducting
- PM Synchronous
- Single-fed Induction
- Double-fed Induction



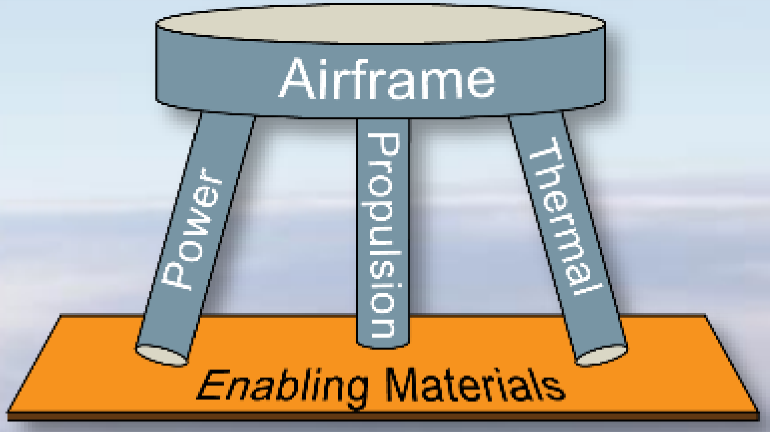




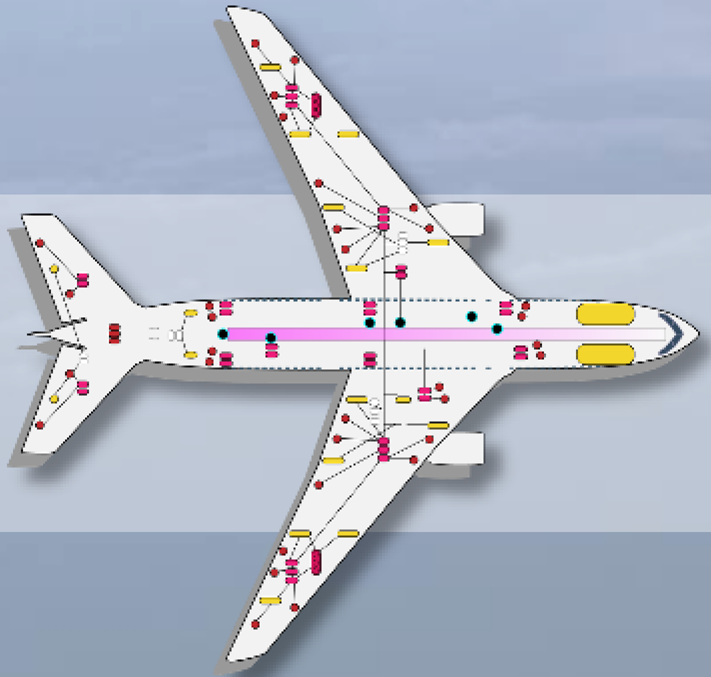
(Beach, NASA)

Power, Propulsion, Thermal, and Airframe Integration

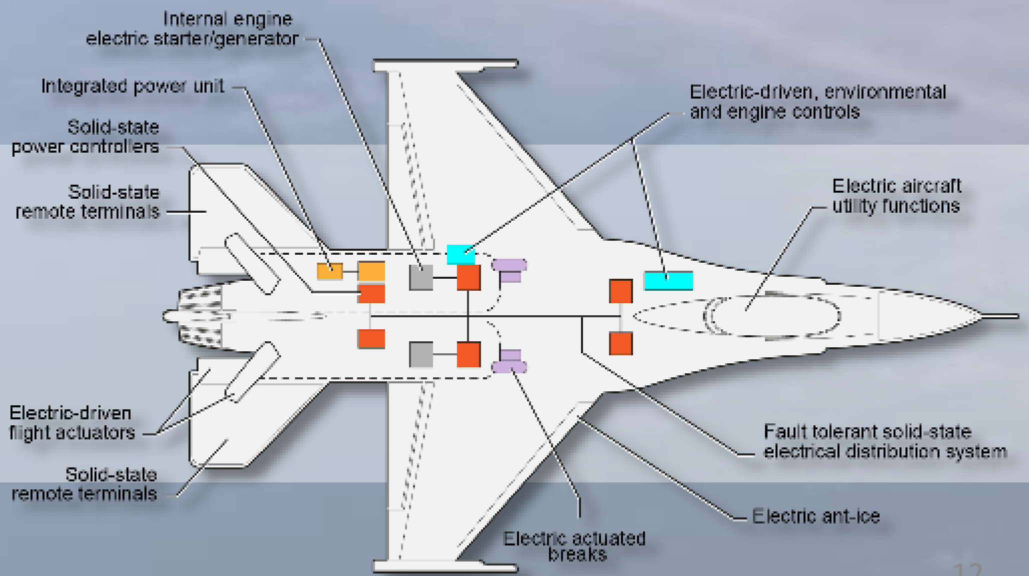
- **Challenge is to highly integrate all systems:**
  - improve fuel efficiency
  - reduce emissions
  - reduce low grade waste heat
  - reduce vehicle mass



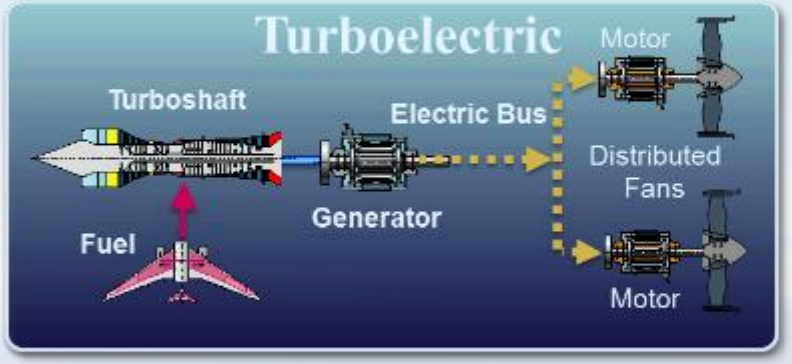
All components must integrate



PM and Induction Machine is a Near-term Technology



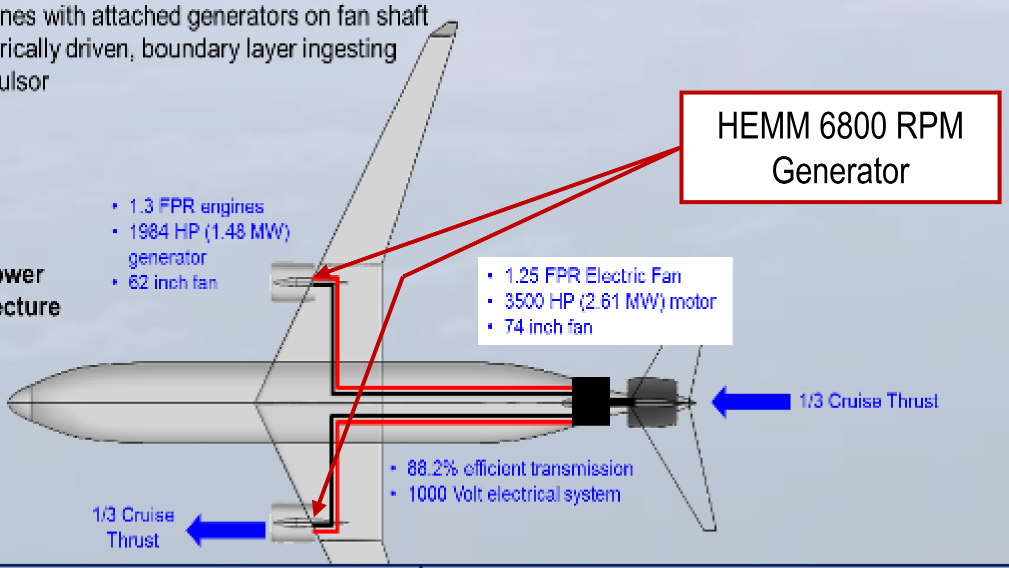
Electric Machine Integration



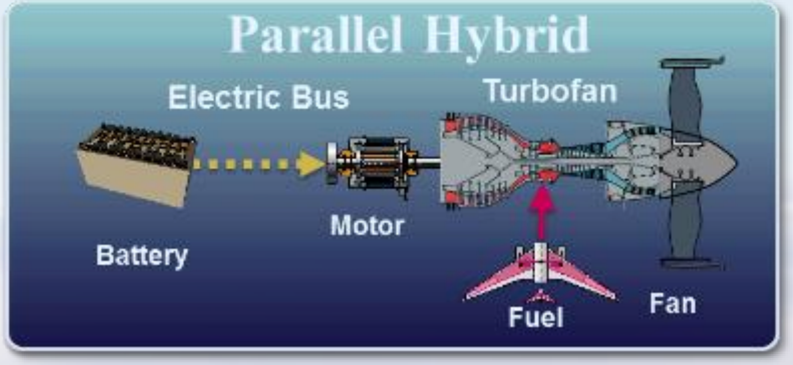
Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL)

- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted N+3 (Far-term) geared turbofan engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor

STARC-ABL Power System Architecture

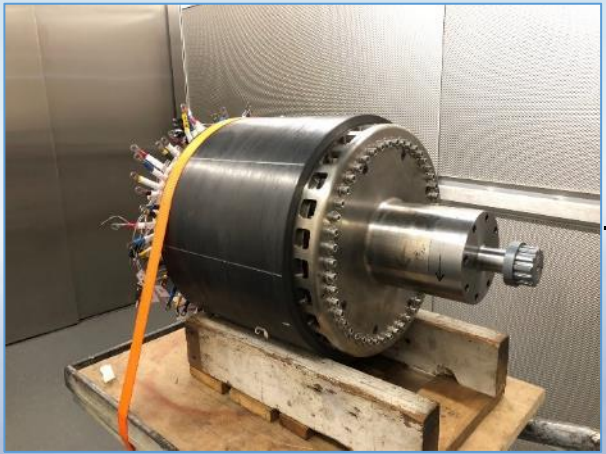


Partial Turbo-electric Benefits From Efficient Generator



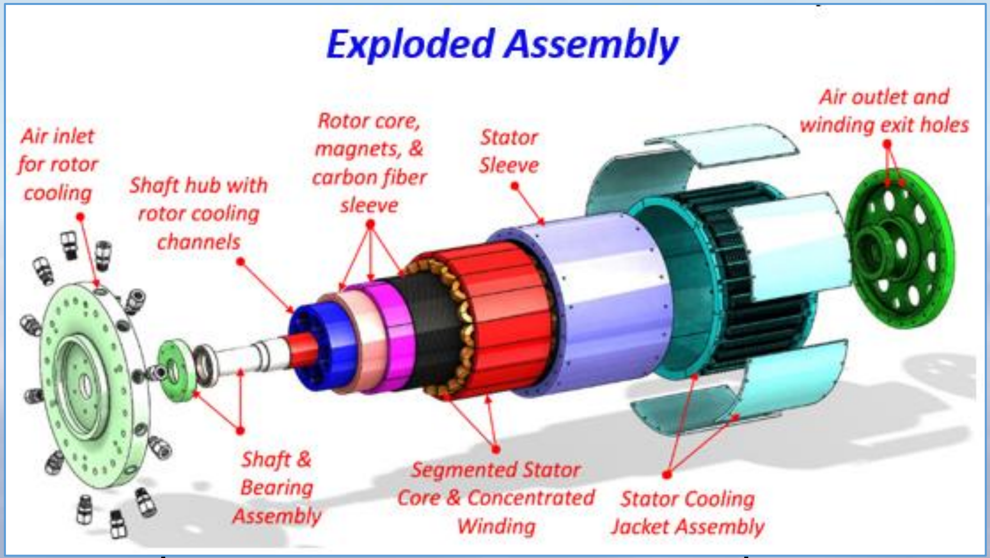
Parallel Hybrid Performance Improves with Energy Storage

Ambient MW Motor Development

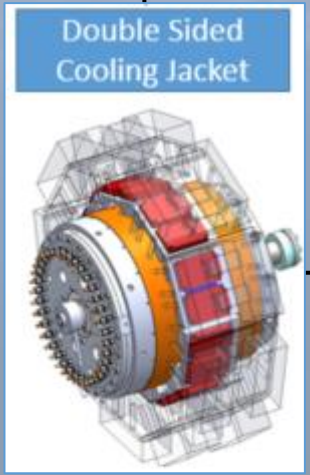


U. Illinois assembled MW Machine ready for testing

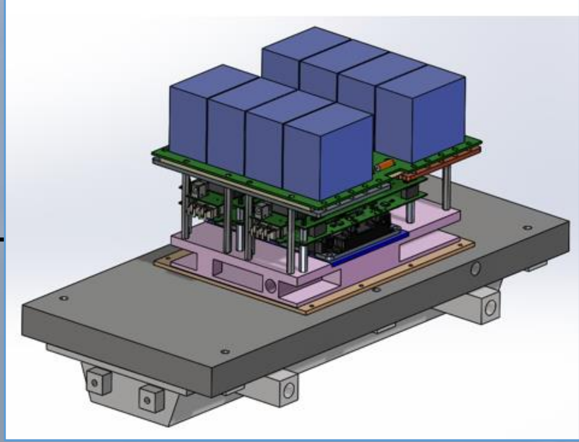
U. Illinois Composite-wrapped Halbach Array Rotor



OSU MW motor connected to electric load machine



Integrated power module with stator cooling



(Provenza/Taylor, NASA)

Ambient MW Inverter

Problem

High voltage 2 kV+ DC system enables lightweight high-efficiency power distribution systems for future hybrid electric aircraft. High voltage altitude capable inverters are essential for such a system.

Objective

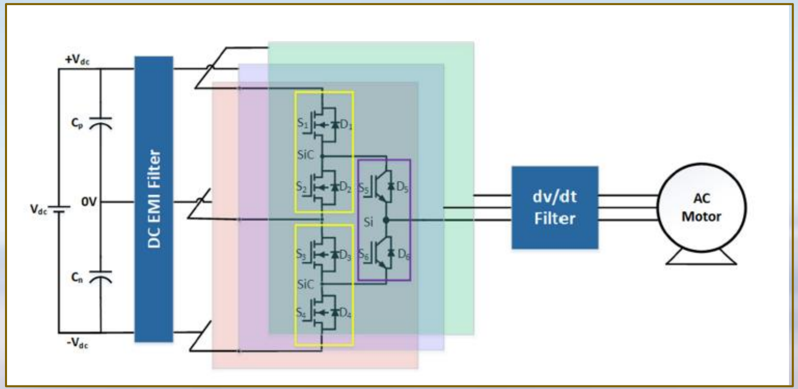
- Develop and demonstrate high voltage SiC MW inverter with altitude capability.
- Retire risks for 2 kV+ DC system for 30+ kft altitude at ambient temperature.
- Retire vibration risk.

Results

Subtask	Deliverable
Develop and test altitude capable components	Components passed altitude screening test and ready for inverter build
Gen3 altitude ready inverter design	Inverter design ready to be built
Sea level test of Gen3 inverter	• Validate power capability of Gen3 inverter • Capture EMI performance of Gen3 inverter
Altitude chamber test of Gen3 inverter	• Establish testing capability for high voltage inverter at altitude • Validate altitude capability of Gen3 inverter
Altitude integration test at NASA NEAT	Gen3 inverter tested with motor generator at NEAT
Gen4 flight ready inverter design	Design of Gen4 inverter to meet shock and vibration and EMI requirements

Significance

Components are developed for high voltage altitude capable inverter. Ongoing work continues to retire risks of employing high voltage inverter in future hybrid electric aircraft.



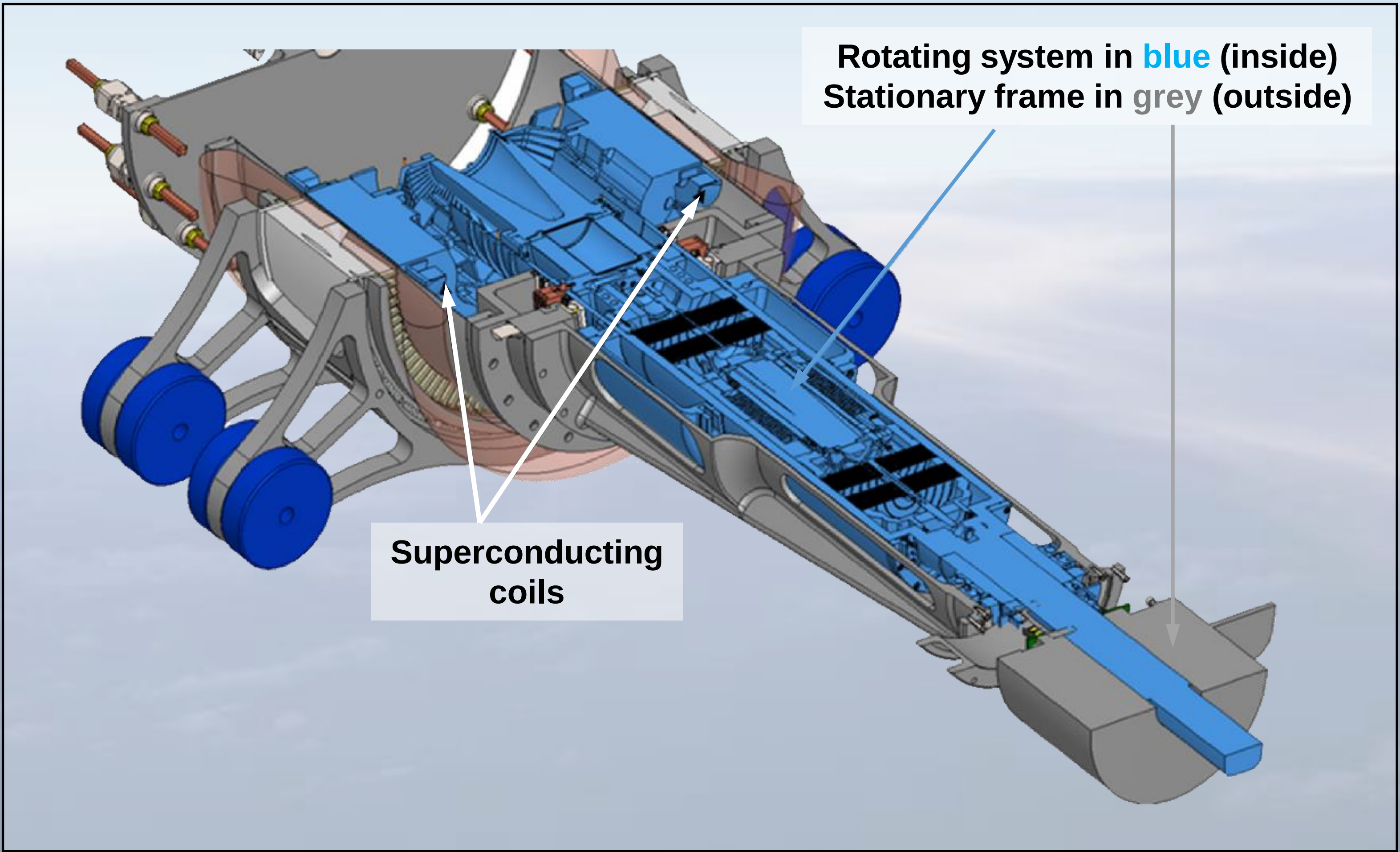
"SiC+Si" hybrid three-phase 3L-ANPC inverter

Gen3 inverter in altitude chamber

dv/dt filter inductor tested for altitude

(Choi, NASA)

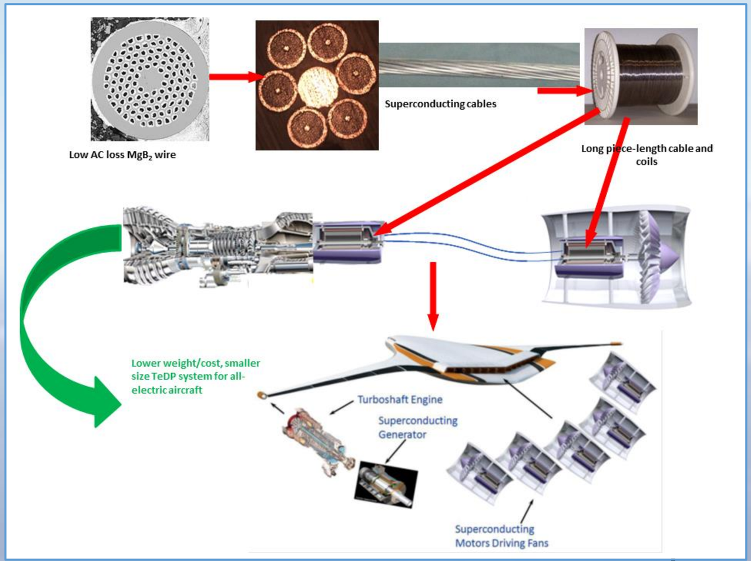
Cryogenic Rotor MW Motor Development



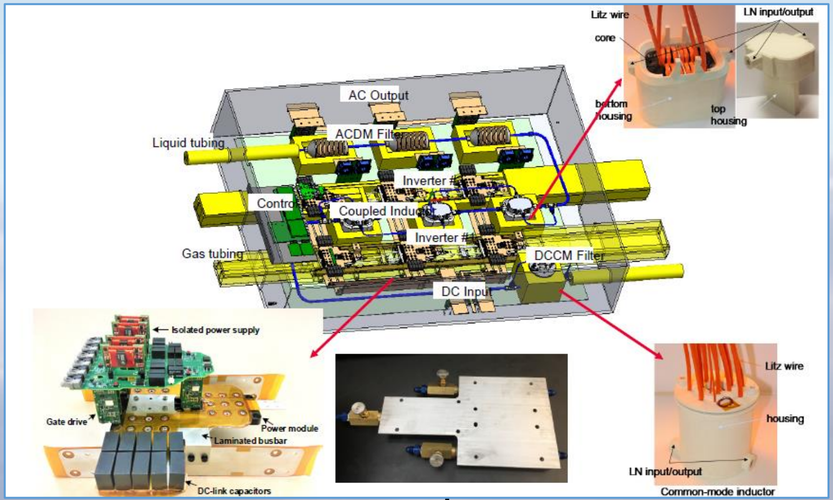
Under 50W Cryogenic Heat Load Expected

(Jansen, NASA)

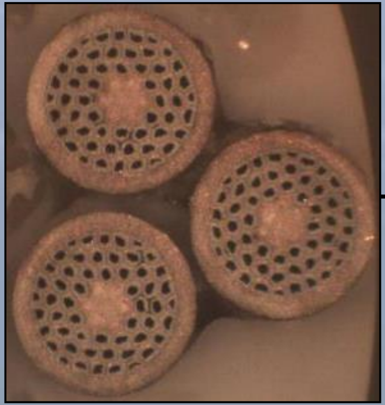
Cryogenic MW Inverter and Coil



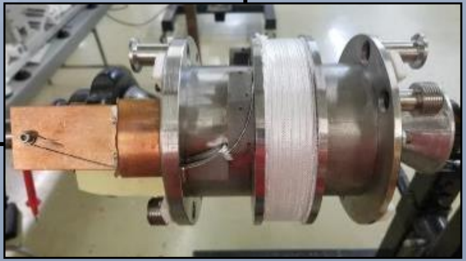
Turbo-electric distributed propulsion system using SC motors and generators with low AC loss MgB_2 cables



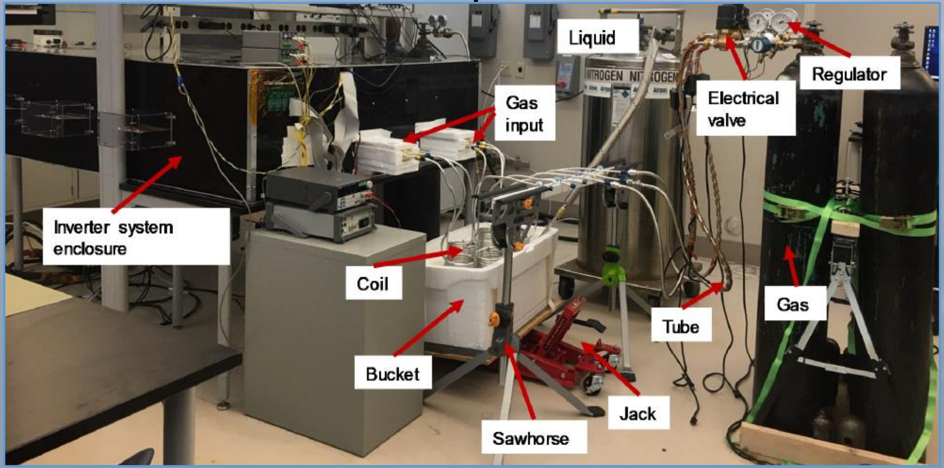
Integrated inverter system



MgB_2 cables used for test coil



Test MgB_2 coil fabrication



1 MW inverter testing setup with cryogenic cooling

(Brown/Choi, NASA)

Improved Motor Reliability

- **External Efforts[1]: 2 Contract Funded Design**

University of Wisconsin via OSU ULI

- Integrated, fault-tolerant motor/drive design for RVLT quadcopter

2) Balcones Technologies vis Phase III NASA STTR

- Developing Brushless Doubly-Fed Machine (BFDM) design for RVLT-class vehicle (100-200 kW)

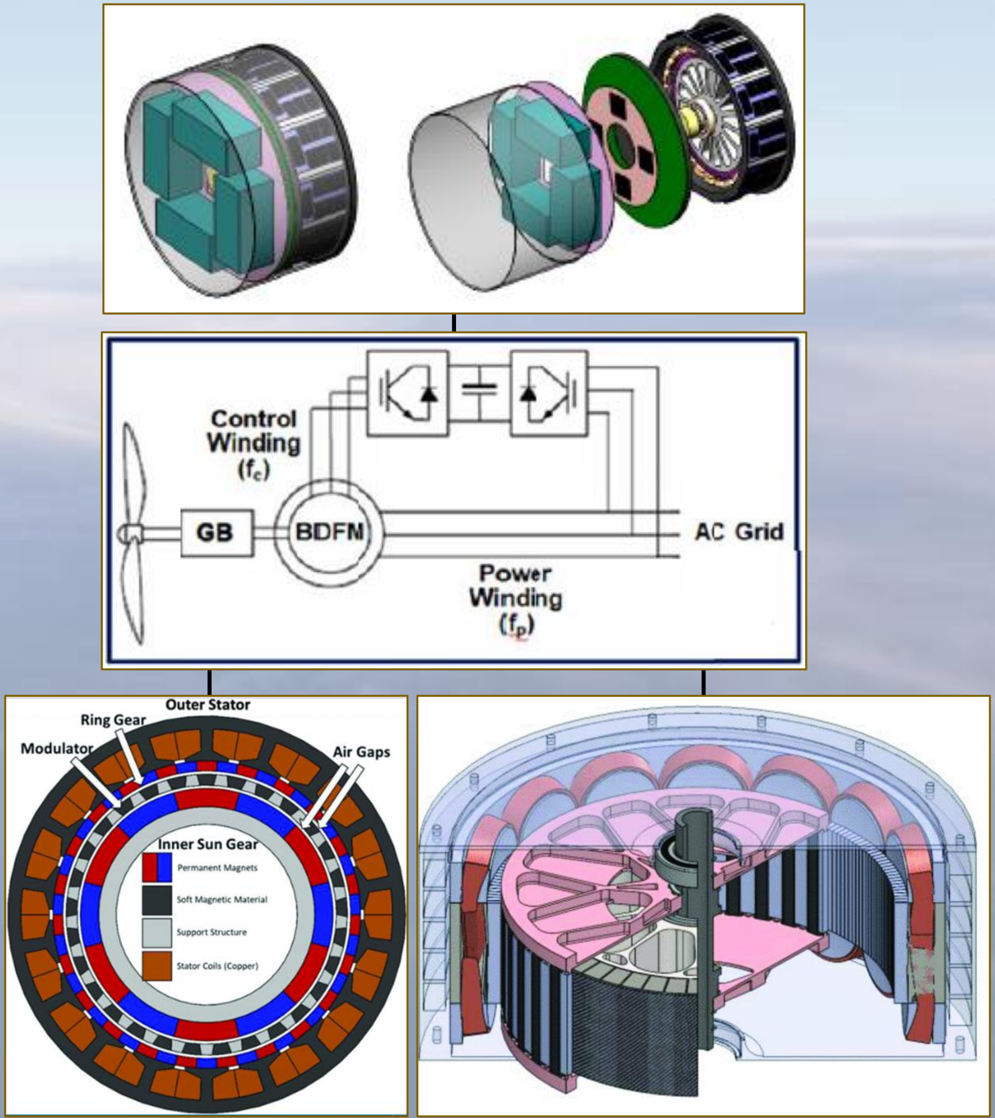
- **Internal Efforts[2]:**

1) Magnetically Geared Motors and Novel Designs

- Exploring trade space of reliable motor topologies for UAM applications using in-house codes.
Example: Outer Stator Magnetically Geared Motor

2) Winding Reliability Model Development

- Developing modeling and experimental capability to explore/predict winding reliability



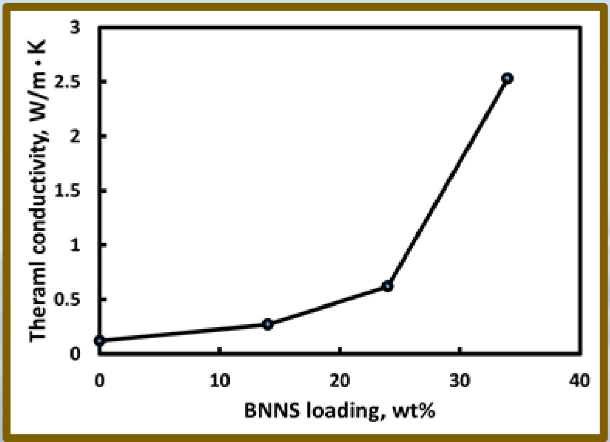
1. J. Swanke, T. Jahns, "Reliability Analysis of a Fault-Tolerant Integrated Modular Motor Drive (IMMD) for an Urban Air Mobility (UAM) Aircraft Using Markov Chains." 2021 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS).
2. T. F. Tallerico, Z. A. Cameron, J. J. Scheidler and H. Hasseeb, "Outer Stator Magnetically-Geared Motors for Electrified Urban Air Mobility Vehicles," 2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), New Orleans, LA, USA, 2020, pp. 1-25.

(Taylor, NASA)

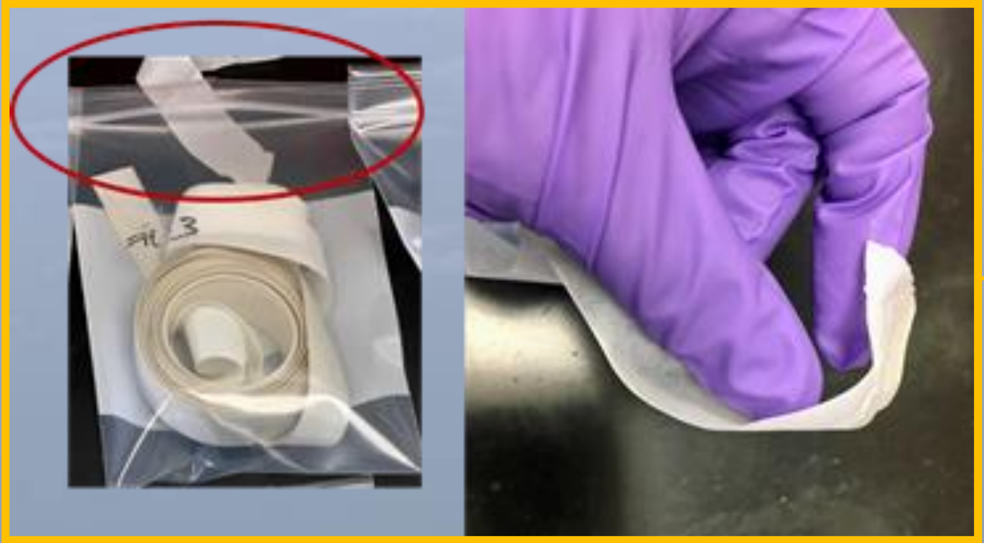
Electric Machine Insulation Solutions

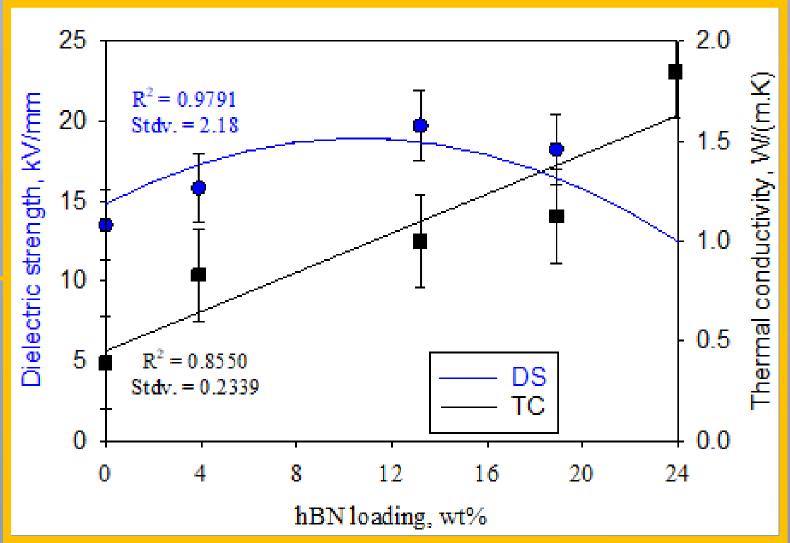
Extruded polymer composite materials offer a unique solution space

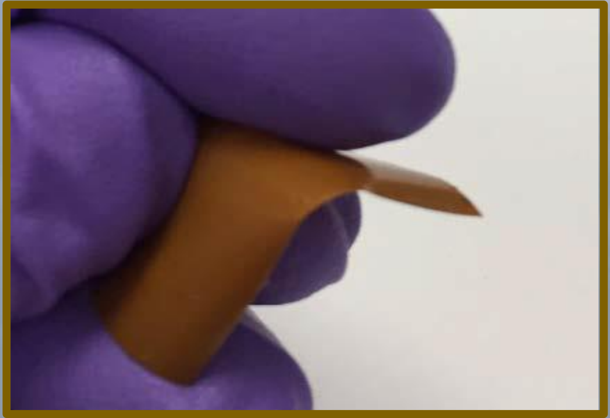
Unlocking the potential of high-power density (>1kW/kg) electric MW scale machines by improving the thermal conductivity electrical insulation while maintaining electrical and mechanical properties



Boron nitride polyimide composites can offer significantly improved thermal conductivity to magnet wire applications







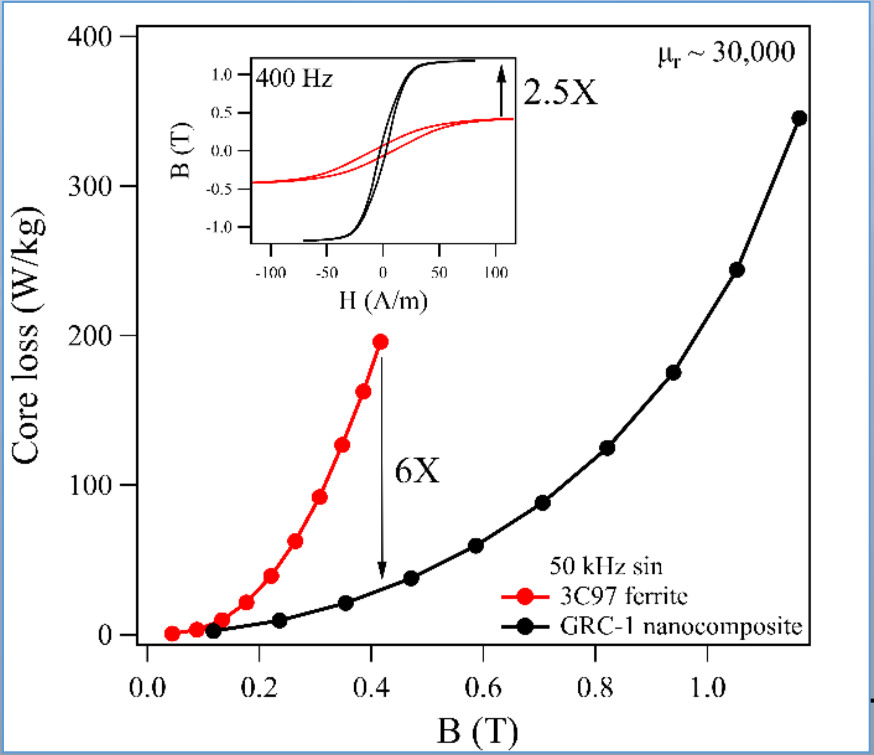
(Woodworth, NASA)

Prototype Inductor Core Development

The selection of commercial passive components for electric propulsion is limited – both in available core materials and size

GRC has ability to design and fabricate nanocomposite cores in custom sizes to meet this need

Example: 15µH 15A$_{peak}$ common mode chokes for NASA's X-57

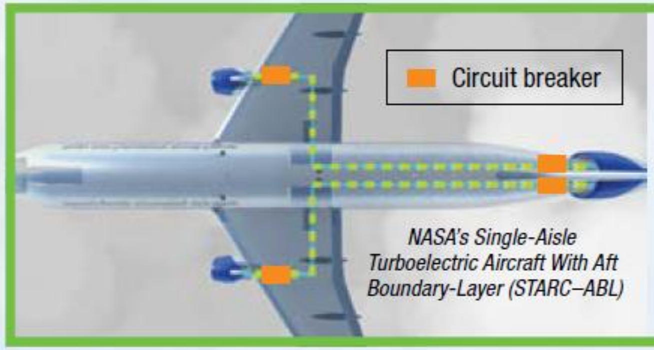


Core material has higher B$_{sat}$ and lower loss compared to MnZn ferrites

Compositions developed with tunable permeability to enable gapless toroid

(Leary, NASA)

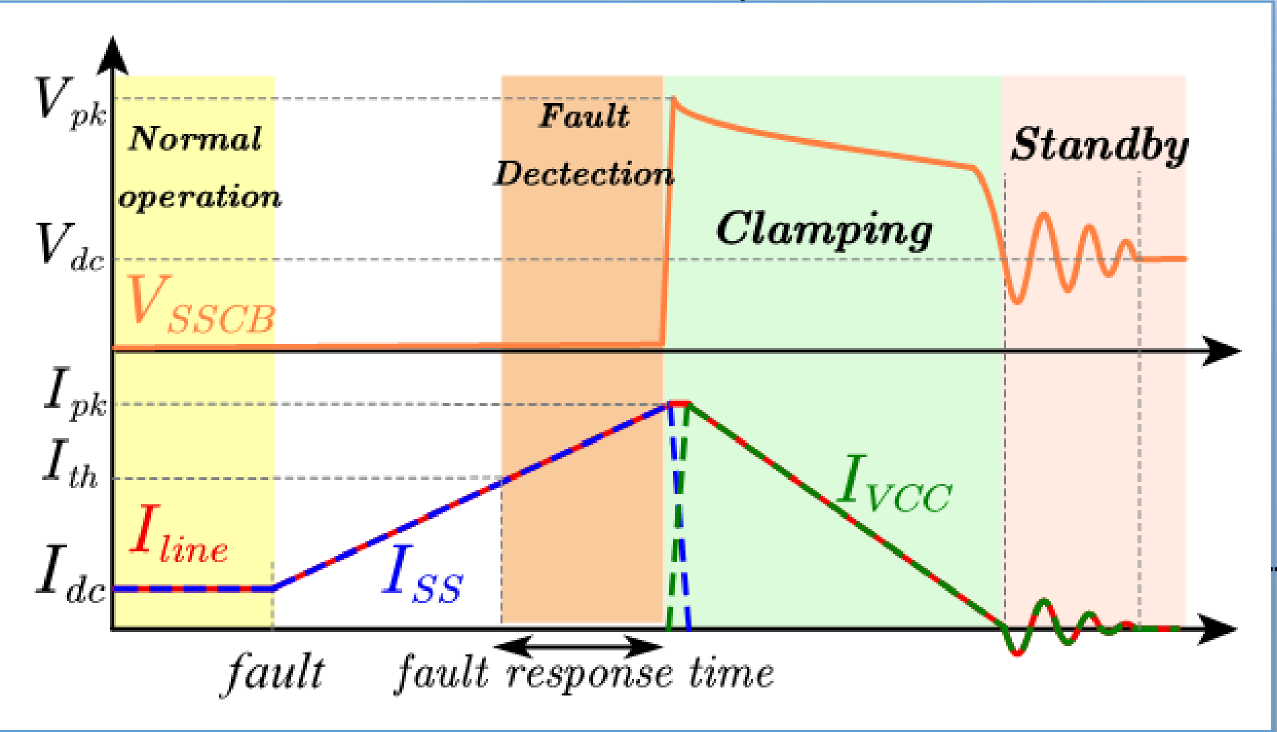
Fault Management Challenge

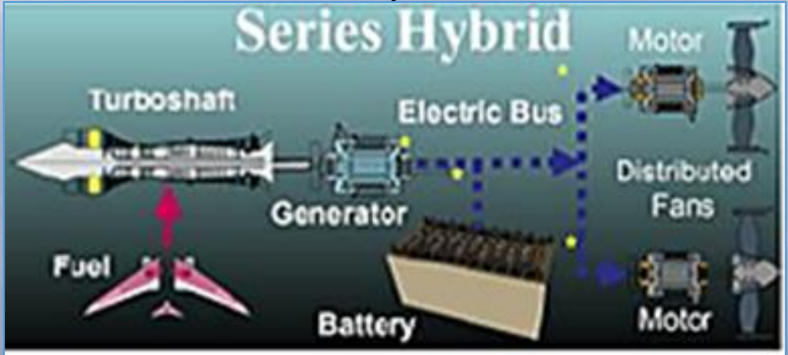


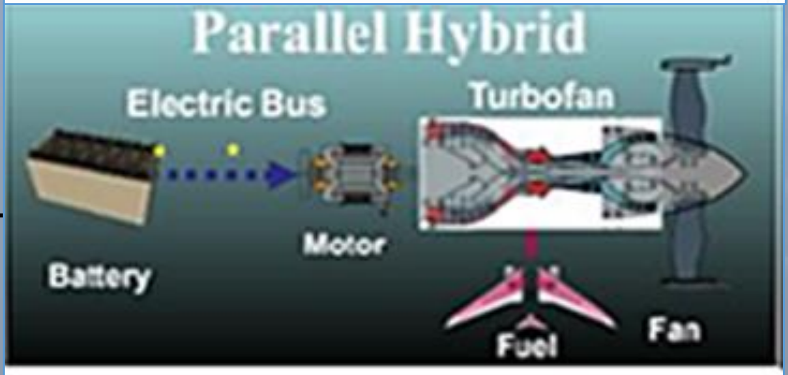
CHALLENGE:

Develop circuit-breaking devices that are...

- Strong enough to stop **megawatts** of energy (around 100 times the energy in a house!)
- Able to respond in just **microseconds**
- **10 times lighter** than anything yet engineered







Fault Condition Response Requirements

- Megawatt DC bus power is essentially a high-power arc welder if a fault condition is not managed quickly enough.

Fault Type	Effect	Response Time Required
IGBT over-current	Damaged circuit	< 500 us
Arcing	Damaged equipment	<1 ms
Over-heating	Damaged plane	<10 ms

Ultra-fast, flight weight, medium voltage circuit breakers will protect passengers, equipment, and circuitry so the aircraft can still be used under a full range of fault situations including:

- **Environment**
  - lightning, bird-strike, wind sheer, turbulence vibration, cosmic ray
- **Operation**
  - engine stall, tail strike, microwave interference
- **Design**
  - insulation fail, rotor burst, equipment failure, fatigue crack, control/software issue

Machine and Fault Management Integration

Machine Type	Fault Management	Specific Power (kw/kg)	Efficient (%)	Benefit	Challenge
PM	SSCB Open Circuit High Voltage	>6	>95	Light-weight and efficient	Fast fault management required – Needs SSCB or advanced controls Low inductance
Induction	De-energizes on open circuit	>4.7	>92	Simple construction Hybrid CB can be used High Inductance	Slower response time Thermal Loads
Wound Field	Rotor field quick cut-off	>5	>96	Highly controllable Hybrid CB can be used Medium Inductance	Rotor thermal management
Partial SC Wound Field	Rotor field quick cut-off	>15	>98	Highly controllable Hybrid CB can be used Medium Inductance	Rotor thermal management

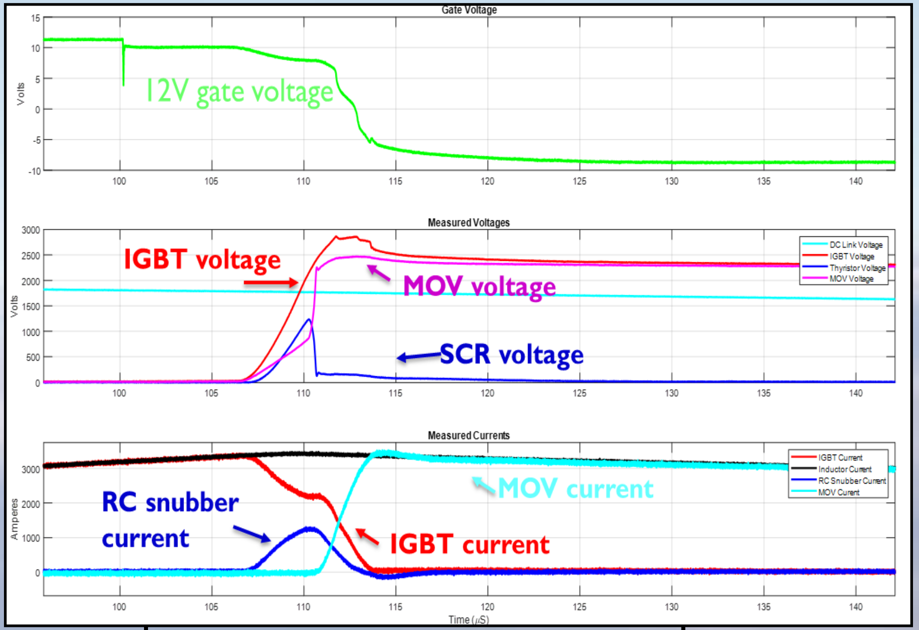
Fault Management Technology Options

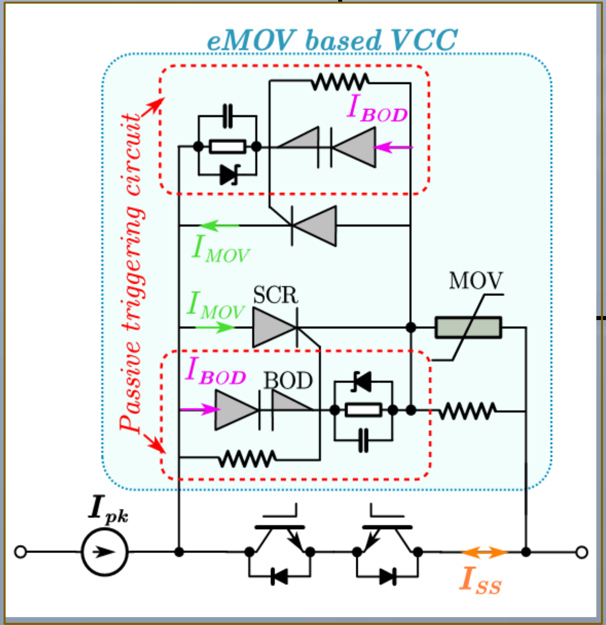
	Mechanical	Solid-State	Hybrid
Device to break current	Mechanical Switch	Semiconductor Devices	Semiconductor Devices and Mechanical Switch
Benefits	Low Conduction Loss	Super-fast response time (<10 us) Simple structure	Low conduction loss Fast response time (1-5 ms)
Limitations	Slow Response Time (50 ms)	**High conduction loss (~0.5%)**	Complexity

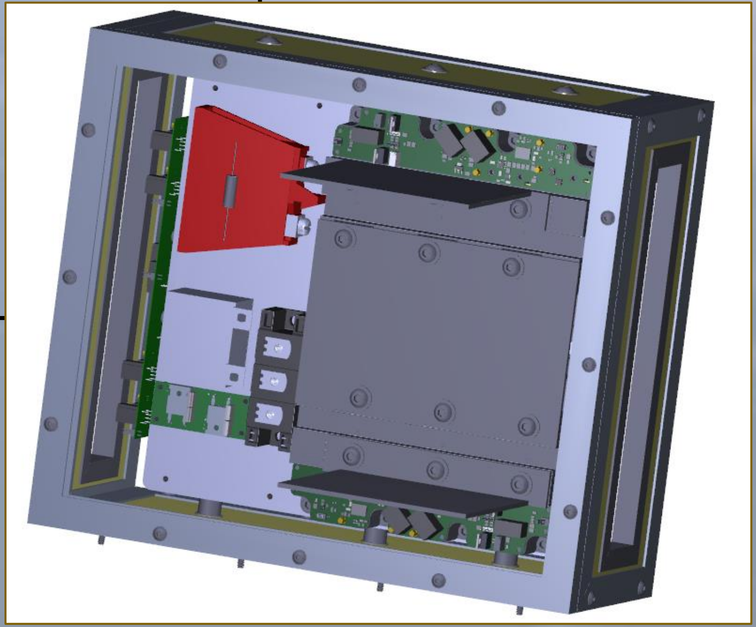
"All [aerospace] machines are PM (radial inner rotor, radial outer rotor, and axial flux)".

Ultra-Fast, Light-Weight Breaker System

- Two IGBTs with anti-parallel diodes are connected in series to carry and break load currents in either direction.
- MOV is connected in parallel with IGBTs to clamp the voltage across IGBTs. MOV's clamping voltage is higher than dc link voltage to reduce the system fault current.
- Two paralleled SCRs are connected in series with MOVs to share MOV voltage in steady state, so lower voltage MOV can be used for efficiency and power density improvement.
- SCRs are turned on right after IGBTs are turned off by passive triggering circuits and can be turned off automatically after the fault currents are cleared.





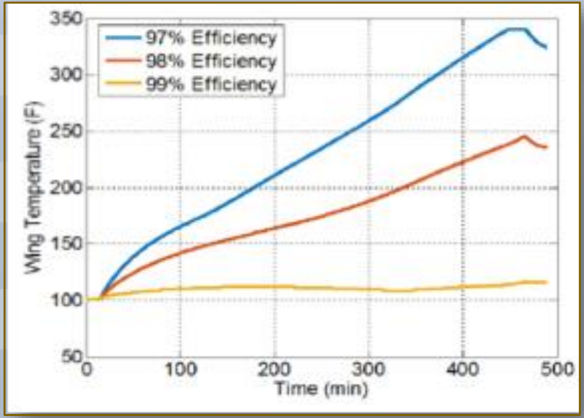


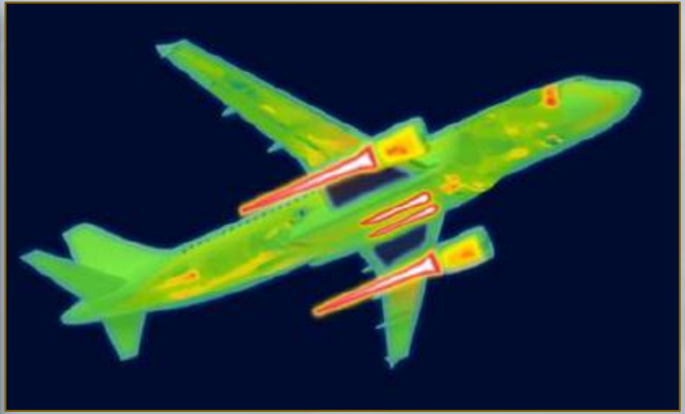
Electric Aircraft Thermal Challenge

Current proposed solutions include:

- Ram air HX
  - adds weight and aircraft drag
- Convective skin cooling HX
  - adds weight, drag, and inefficient
- Dumping heat into fuel
  - limited thermal capacity
- Dumping heat into lubricating oil
  - limited thermal capacity
- Active cooling
  - adds weight and consumes engine power
- Phase change cooling
  - adds weight and limited thermal capacity
- Heat pipe, pumped multiphase, vapor compression
  - adds weight and consumes engine power

Energy Transfer Medium	**Limits**	**Scale**
Electrical	Voltage, Copper Mass and Heat	I^2R
Mechanical	Lubrication, Vibration, Heat, Mass	$0.5\ \tau\omega^2$
Fluid	Freezing, Pump, Impurities, Heat, Mass	$\dot{m}\ C_p$T
Phase Change/Vapor	Gravity, Orientation, Distance, Freezing	<1 m
Acoustic	Design Challenge, Some Heat	$0.5 * pv^2$



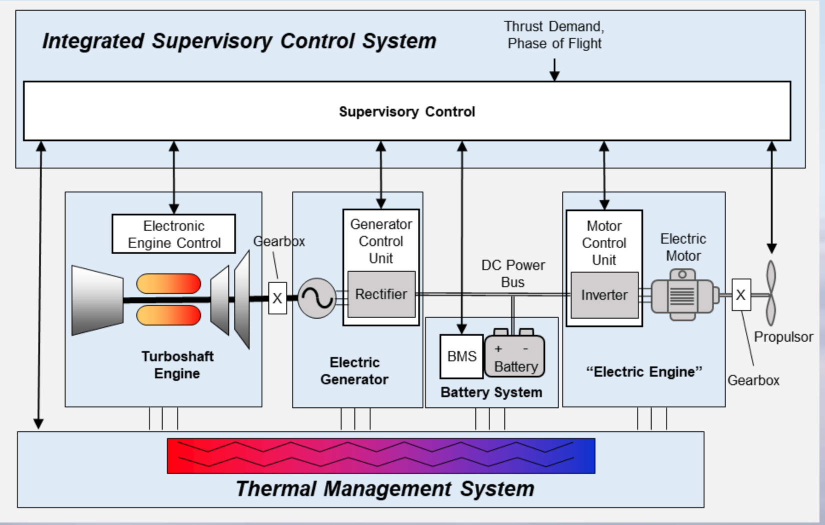


P.C. Krause

50kW to >800kW of low-grade thermal heat trapped within composite aircraft body

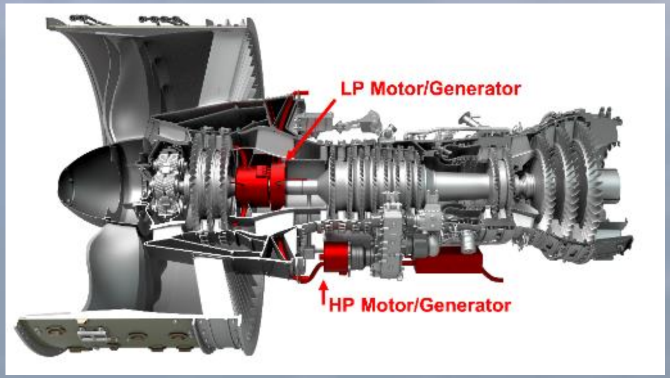
Electrified Aircraft Propulsion System-Level Controls

- Electrified aircraft propulsion (EAP) systems are complex and highly integrated – presents both control design challenges and opportunities
- System-level supervisory control enables:
  - Optimal energy management (hybrid designs)
  - Fault management through reversionary control modes
  - System-level thermal management approaches



Notional Hybrid Electric Propulsion System with Supervisory Control

- Electrification is transforming aircraft engine control design
- NASA's Turbine Electrified Energy Management (TEEM) control methodology:
  - Applies electric machines to supply or extract engine shaft power
  - Promotes engine operability and suppresses off-design operation naturally associated with engine transients
  - Enables design of lighter engines with improved efficiency



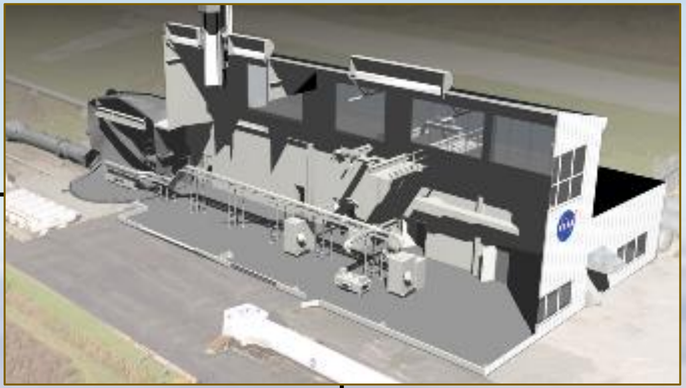
Conceptual advanced geared turbofan with electric machines on low and high spool shafts

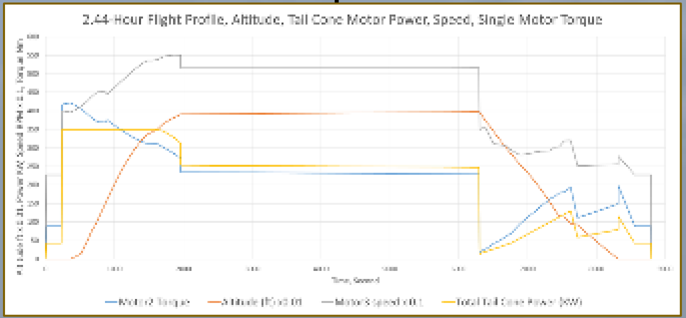
(Simon, NASA)

Technology Readiness Level Testing Challenge

Reconfigurable Powertrain Testbed for Fault Testing

- Located at NASA Glenn Plum Brook Station in the recently refurbished Hypersonic Tunnel Facility (HTF)
- Supports full-scale megawatt powertrain testing under actual flight scenarios with cryogenic fuel, high voltage, large wingspan, electromagnetic interference, and high altitude





(Haglage, NASA)

TRL maturation:

- **High voltage bus architecture –**
  Insulation, geometry, 600V up to 4500V
- **High power MW Inverters, Rectifiers-**
  Commercial, In-House, NRAs
- **High power MW Motors, Generators-**
  Commercial, In-house, NRAs
- **System Communication –**
  Aircraft CAN, Ethernet, Fiber-optics
- **System EMI Mitigation and Standards –**
  Shielding, DO-160G, MIL-STD-461
- **System Fault Protection –**
  Fuse, Circuit Breaker, Current Limiter
- **System Thermal Management –**
  Active/Passive, Ambient/Cryo
- **Altitude Integration-**
  Cosmic, creepage, partial discharge

Powertrain Lessons Learned:

- **EMI shielding is critical for safe and proper operation of the powertrain even with DO-160G compatible equipment.**
- **Federated fault response with localized feedback/controls are important for orderly shutdown sequencing.**
- **System interactions between components must be tested to account for common modes, grounding loops, and resonant conditions**
- **Optical fiber and digital instrumentation are required for robust communication and sensors**
- **Higher voltage and current present new issues such as insulation resistance breakdown and power quality challenges when operating near rated equipment limits**
- **Shielding throughout the powertrain limits the ability to acquire data from transducers forcing calculated software measurements.**

Conclusion

NASA IS INVESTING IN ELECTRIFIED AIRCRAFT PROPULSION (EAP) TO ENABLE A NEW TECHNOLOGY S-CURVE OF INNOVATION IN AVIATION

NASA is broadly investing in Electrified Aircraft Propulsion (EAP)

NASA investments are guided by a combination of potential market impacts and technical key performance parameters.

The impact of EAP varies by market and NASA is considering three markets: on-demand mobility, regional and national/international air transportation.

Technical advances in key areas have been made that indicate EAP is a viable technology.

Flight research is underway to demonstrate integrated solutions and inform standards and certification processes.

Additional work is needed to transition the technology to a commercial product and further improve the technology to realize the benefits across the world.

Feasible Vehicle Class Driven by Powertrain Specific Power and Efficiency and Integrated Vehicle Design Optimization

Power, Propulsion, Thermal, and Airframe Integration Key

The Institution of Engineering and Technology

NASA